

Fatigue in Operational Settings: Examples from the Aviation Environment

MARK R. ROSEKIND, *NASA Ames Research Center*, PHILIPPA H. GANDER, *San Jose State University Foundation*, DONNA L. MILLER and KEVIN B. GREGORY, *Sterling Software*, ROY M. SMITH, KERI J. WELDON, ELIZABETH L. CO, and KAREN L. McNALLY, *San Jose State University Foundation*, and J. VICTOR LEBACQZ, *NASA Ames Research Center, Moffett Field, California*

The need for 24-h operations creates nonstandard and altered work schedules that can lead to cumulative sleep loss and circadian disruption. These factors can lead to fatigue and sleepiness and affect performance and productivity on the job. The approach, research, and results of the NASA Ames Fatigue Countermeasures Program are described to illustrate one attempt to address these issues in the aviation environment. The scientific and operational relevance of these factors is discussed, and provocative issues for future research are presented.

INTRODUCTION

Today, 24-h operations are a critical component of maintaining our technological society. Many different types of occupations and industries rely on round-the-clock operations, including health care, public safety, service and manufacturing industries, military operations, and transportation. Estimates are that one in five American workers is a shiftworker, working some form of nonstandard or altered work schedule (Office of Technology Assessment, 1991). These 20 million American shiftworkers are exposed to major disruptions in their physiology, social activities, and family lives. The principal physiological disruption occurs in two areas: sleep and circadian rhythms.

Sleep is a vital physiological function, and obtaining even 1 h less than required can affect waking levels of sleepiness (Carskadon and Dement, 1982). Sleep loss may be acute or, if occurring continuously over time, may result in a cumulative sleep debt (Roth, Roehrs, Carskadon, and Dement, 1989).

The suprachiasmatic nucleus in the hypothalamus is a pacemaker for 24-h physiological and behavioral rhythms. Circadian (about 24 h) rhythms govern sleep/wakefulness, motor activity, hormonal processes, body temperature, performance, and many other factors. Core body temperature is often used as a biological marker of circadian position and is related to the fluctuations seen in sleep/wakefulness, performance, hormone secretion, digestion, and other physiological activities. The minimum of the body temperature rhythm (which typically occurs at 3:00 to 5:00 a.m. daily) is associated with sleep,

¹ Requests for reprints should be sent to Mark R. Rosekind, NASA Ames Research Center, Mail Stop 262-4, Moffett Field, CA 94035-1000.

low motor activity, decreased performance, and worsened mood. Disturbances of 24-h biological rhythms may be acute or continue over long periods, resulting in chronic desynchronization between different physiological systems. (For background in this area, see Dinges, 1989; Mistlberger and Rusak, 1989; Monk, 1989.)

Cumulative sleep loss and circadian disruption can lead to decreased waking alertness, impaired performance, and worsened mood (Bonnett, 1985; Broughton and Ogilvie, 1992). Individuals often use the word "fatigue" to characterize these experiences. Estimates suggest that 75% of night workers experience sleepiness on every night shift, and for 20% of them, sleepiness is so severe that they actually fall asleep (Akerstedt, 1991). Although many factors may affect the subjective report of fatigue (e.g., workload, stress, environmental factors), the most substantial empirical data suggest that the two principal physiological sources of fatigue are sleep loss and circadian disruption.

Fatigue is a concern in many operational settings that require 24-h activities (Office of Technology Assessment, 1991). Decreased performance related to sleep loss and circadian disruption has been implicated in some major disasters, such as the Exxon Valdez, Three Mile Island, and Bhopal accidents (Office of Technology Assessment, 1991). Although the potential risks of sleep loss and circadian disruption exist, they do not diminish society's need for continuous 24-h operations. Therefore, it is critical that the extent and impact of fatigue in operational settings be understood. Strategies and countermeasures should be developed and empirically evaluated to determine approaches that will maximize performance and alertness and help to maintain an adequate margin of safety.

This article describes a National Aeronautics and Space Administration (NASA) pro-

gram, the approach, methods, research, and results of which are designed to address these issues in the aviation environment. It provides an example of how, in one mode of transportation, fatigue has been empirically studied to provide relevant data to both the scientific and operational communities.

NASA AMES FATIGUE COUNTERMEASURES PROGRAM

Program Goals and Research Approach

In 1980, responding to a congressional request, NASA Ames Research Center sponsored a workshop that examined whether "the circadian rhythm phenomenon, also called jet lag," was of concern (National Aeronautics and Space Administration, 1980, p. 1). The workshop participants concluded that "there is a safety problem, of uncertain magnitude, due to transmeridian flying and a potential problem due to fatigue in association with various factors found in air transport operations" (abstract). The NASA Ames Fatigue/Jet Lag Program (later called the Fatigue Countermeasures Program) was created to determine the magnitude of the problem and its operational implications. Three program goals were established, which continue to guide research efforts: (1) to determine the extent of fatigue, sleep loss, and circadian disruption in flight operations; (2) to determine the impact of these factors on flight crew performance; and (3) to develop and evaluate countermeasures to mitigate the adverse effects of these factors and to maximize flight crew performance and alertness.

The overall research approach has been to integrate data collected from field studies during regular flight operations with full-mission, high-fidelity flight simulation studies and with results from controlled laboratory experiments. Each of these research approaches has strengths and weaknesses from both a scientific and an operational

viewpoint. Field studies may more accurately reflect real-world conditions but are inherently difficult to conduct because, for example, research protocols must not interfere with regular operational procedures or safety. Also, it is virtually impossible to control all potential contributory factors in field studies, and there are limitations to the empirical measures that can be tolerated by subjects in their usual work environment.

Laboratory studies provide a controlled environment for manipulating specific independent variables and determining the outcome in precise ways. However, attempts to generalize these findings to the more complex operational setting may greatly limit the operational relevance of laboratory studies that cannot incorporate all of the potential intervening variables.

Full-mission, high-fidelity flight simulation studies provide a unique opportunity to manipulate the specifics of a trip scenario and measure a wide range of flight variables. However, constraints on the simulation environment must be considered (e.g., realism, costs). Clearly, the integration of all three approaches in a single program has important advantages, and the program has conducted studies using each of these research approaches to capitalize on their unique strengths.

Measures

The program uses a diverse range of empirical measures to evaluate fatigue. In any given study, the measures are determined by the specific hypotheses and objectives of that particular study. The initial field studies examining the extent of fatigue, sleep loss, and circadian disruption utilized a combination of self-report and physiological measures. The self-report measures included a background questionnaire and a pilot's daily logbook.

The background questionnaire collected

demographic data and information on flight experience, sleep, meals, exercise, and general health. It also included some standardized surveys, such as that for personality style.

The pilot's daily logbook, which is pocket-sized, contains information about flight and duty times, sleep quantity and quality, mood, meals, exercise, physical symptoms, and comments (e.g., operational events, environmental factors). These data are collected a maximum of three days prior to a trip schedule, throughout a trip, and for a maximum of four days after the trip.

The first physiological variable assessed was core body temperature, which allowed the determination of circadian phase and measurement of amplitude. An ambulatory recorder (Vitalog, Inc.) collected continuous temperature data via a rectal thermistor, heart rate information via chest electrode placements, and activity detected by a motion sensor worn on the nondominant wrist. This portable recorder collected and stored the data for up to 10 days.

Over the years, the sophistication and range of measures has increased. Continuous portable recording of electroencephalographic (EEG), electro-oculographic (EOG), and electromyographic (EMG) activity is obtained using an Oxford Medilog 9200 recorder. This instrument provides up to eight channels of physiological data, which are continuously collected in analog form onto a high-quality cassette tape. The Medilog can collect continuous data on one tape for up to 24 h. The tape is later played back on a scanning system that allows detailed analysis of standardized sleep variables (e.g., sleep latency, total sleep time, amounts of rapid eye movement [REM] and non-REM sleep, and awakenings).

The Medilog can provide both sleep and wakefulness data. The EEG information can be analyzed for EEG frequency changes (e.g.,

alpha and theta activity), and the EOG data reflect slow eye movements, which are associated with physiological sleepiness during wakefulness (Akerstedt and Gillberg, 1990).

In addition to these physiological measures, a recent study incorporated a vigilance performance measure that uses reaction time to assess sustained attention (Dinges and Powell, 1985, 1988). This psychomotor vigilance task (PVT) is a 10-min simple reaction time test that probes central nervous system (CNS) capability. It has been demonstrated to be sensitive to the effects of sleep loss and circadian disruption and does not have a significant learning curve, unlike many other performance tests (Dinges and Kribbs, 1991).

The PVT data are especially useful as a metric because they can be compared with previous findings from sleep deprivation and sleep disorder studies. The PVT does not represent a specific flight performance variable. Instead, it provides a measure of CNS capability, especially of sustained attention and vigilance performance, which are important factors in many operational settings, including aviation.

New measures are added as study objectives expand into different areas. For example, an upcoming project will require the measurement of noise levels with a sound pressure meter during flight and blood oxygen saturation using an oximeter during sleep. The principal measures used were:

- Background questionnaire (e.g., demographics, personality)
- Survey/questionnaire data (e.g., operational issues)
- Logbook subjective report (e.g., pilot's daily logbook)
- Observational/behavioral data (e.g., cockpit observer log)
- Physical performance and mental functioning tests (e.g., psychomotor vigilance task)
- Long-term continuous recording of motor activity (actigraphy)
- Long-term continuous recording (via Vitalog) of physiological parameters (e.g., core body temperature, heart rate)

Continuous physiological recording (via Medilog) of brain (EEG), eye (EOG), and muscle (EMG) activity

Typically, one or two NASA researchers/observers accompany volunteer pilots during a trip to collect the measures and provide guidance regarding the protocol.

Over the past 12 years, studies have been conducted in a variety of aviation and controlled laboratory environments and in one full-mission flight simulation. These projects were often labor intensive, spanned several years from design to implementation to analysis and reporting of results, and often involved collaborations. Support and collaboration in the United States came from the Federal Aviation Administration (FAA), the National Transportation Safety Board (NTSB), air carriers, pilots, pilot unions, and the military. Some of the international studies involved worldwide collaborations with research and flight operations groups from the United Kingdom, Germany, Japan, and other countries. References reporting the results from many of the NASA studies and other significant program publications are provided in the appendix.

The results of these studies have been collectively organized into an extensive database that encompasses data from more than 500 volunteer pilots. This database allows unique comparisons between operational environments in which similar measures were taken.

Another critical factor in successfully collecting these data has been the assurance of anonymity and confidentiality for all of the participants. After volunteering for a study, a pilot would receive an identification number, and no name would ever be associated with any of the data collected.

RESEARCH EXAMPLES

Three studies will be highlighted to provide examples of the research approach, measures,

and findings and the operational relevance of the data.

Short-Haul Commercial Operations

This study was conducted to examine the extent of sleep loss, circadian disruption, and fatigue engendered by flying commercial short-haul air transport operations (flight legs less than 8 h; see Gander, Graeber, Foushee, Lauber, and Connell, in press). In this study, 74 pilots from two airlines were studied before, during, and after three- and four-day commercial short-haul trips. All flights took place on the East Coast of the United States and occurred throughout the year. Of the pilots contacted about the study, 85% agreed to participate. As a group, the pilots averaged 41.3 years of age and had, on average, 14.6 years of airline experience.

Physiological data (core body temperature and heart rate) and motor activity were obtained every 2 min with the Vitalog portable biomedical monitor. Using the pilot's daily logbook, subjects provided subjective ratings of fatigue and mood every 2 h while awake and recorded their sleep episodes and other activities (e.g., meals, exercise, duty time). All subjects completed a background questionnaire, and a NASA cockpit observer accompanied crews during trip schedules.

The specific daytime and evening trips studied were selected so as to provide information about the upper range of fatigue reported by pilots in these operations. Common features of the trip schedules included early report times (i.e., for duty) and multiple flight legs (average 5.5/day) over long duty days. The trips averaged 10.6 h of duty per day and involved an average of 4.5 h of flight time. One third of the duty periods studied were longer than 12 h. The average rest period was 12.5 h long and usually occurred progressively earlier in the day across successive trip days.

Data from the daily logbook demonstrated

that during trip nights, pilots took about 12 min longer to fall asleep, slept about 1.2 h less, and awoke about 1.4 h earlier compared with their pretrip sleep patterns. The pilots reported this trip sleep as lighter and poorer (with more awakenings) than pretrip sleep. Subjective fatigue and mood were worse during layovers than before or after the trip or during flights. Significant time-of-day effects were found for fatigue, negative emotions, and activation ratings. In the first three ratings of the day following awakening, fatigue and negative emotion ratings were low. Thereafter they increased and reached their highest values in the final rating prior to sleep. Predictably, activation ratings showed the inverse of this pattern.

On trip days, pilots consumed more caffeine (mean = 3.4 servings) than on pretrip days (mean = 1.9 servings) or posttrip days (mean = 2.7 servings), presumably to maintain alertness during operations. Caffeine was consumed primarily in the early morning, which is associated with the earlier wake-up and duty times, and also during the midafternoon peak in physiological sleepiness. During the trip schedule more alcohol (mean = 1.6 servings) was consumed than on pretrip (mean = 0.5 servings) and posttrip (mean = 1.0 servings) days. It can be assumed that pilots consumed the alcohol only after coming off duty (presumably to unwind after a long duty day), and in accordance with federal aviation regulations. During trips, more snacks were consumed, and they were consumed earlier in the wake period.

For 72 pilots flying 589 legs, heart rates obtained during takeoff, descent, and landing were compared with midcruise values. The pilot flying had greater increases in heart rate during descent and landing than did the pilot not flying. This increase was greater under instrument flight rule than under visual flight rule conditions.

This was one of the first field studies

conducted by the NASA program, and it provides a unique insight into the physiological and subjective effects of flying short-haul commercial operations. It demonstrated that these measures could be obtained in an operational environment without disturbing regular performance of duties. The study results suggest several significant operational considerations regarding fatigue. For example, the data showed that the daily duty durations were double the flight durations and that one third of the duty periods were longer than 12 h. Findings from this study suggest that limitations on duty time should be considered, just as pilot flight times are currently limited by federal aviation regulations. Also, the practice of making pilots report for duty earlier on successive trip days, requiring earlier wake-up times, interferes with obtaining adequate sleep. Even when the layovers were relatively long, the circadian system would generally inhibit falling asleep earlier, and hence a significant amount of sleep would be lost during trip nights. Therefore, when possible, duty on successive trip days should begin at the same time or even begin progressively later, moving with the natural tendency of the biological clock to extend the day.

Finally, alcohol is known to disrupt sleep dramatically and therefore contributes to the poor quantity and quality of sleep obtained on trip nights. Alternate ways to unwind after duty and to promote sleep should be identified and offered (e.g., cognitive-behavioral relaxation approaches).

Long-Haul Commercial Operations

This study examined how long-haul (>8 h) flight crews organized their sleep during a variety of international trip patterns and how duty requirements, local time, and the circadian system affect the timing, quantity, and quality of sleep (Gander, Graeber, Connell, and Gregory, 1991). Duty requirements and

local time can be viewed as external/environmental constraints on time available for sleep, whereas the internal circadian system is a major physiological modulator of sleep duration and quality.

Subjects were 29 male flight crew members (average age = 52 yrs) flying Boeing 747 aircraft on one of four commercial international trip patterns. This report combined the data from the four trip schedules. The pilot's daily logbook was completed prior to, during, and following the trip to collect self-reports of duty times and of sleep timing, duration, and quality, and so on (i.e., the same data as in the short-haul study). Core body temperature, heart rate, and activity using the Vitalog portable biomedical monitor were collected every 2 min. The core body temperature, measured with a rectal thermistor, was used as a marker of the underlying circadian time-keeping system.

On average, the duty periods lasted about 10.3 h and were followed by 24.8 h of layover. During layovers there were generally two sleep episodes. The average sleep/wakefulness pattern was 19 h awake, 5.7 h of sleep, 7.4 h awake, and 5.8 h of sleep. Pilots generally reported that the first sleep of the layover was of better quality and that they fell asleep more easily and obtained deeper sleep than in the subsequent sleep episode. As the length of sleep increased, there was a concomitant increase in sleep quality ratings. The circadian system appeared to exert a greater influence on the timing and duration of the first sleep episode than on that of the second sleep of a layover, with a preference for sleeping during local night and/or waking up after the temperature minimum. The exception was after eastward flights that crossed five or more time zones and produced a high accumulated sleep debt. The time of falling asleep for the second sleep episode was related to the amount of sleep already obtained. It typically occurred during local night, and the duration

was related to the remaining time available before duty. The duration of both sleep episodes was longer when crew members fell asleep earlier with respect to their circadian temperature minimums.

Subjective reports of naps taken during layovers were obtained from the daily logbook. When the first sleep episode of a layover was identified as a nap, it averaged 2 h in length, was generally longer than other naps, and followed significantly longer periods of wakefulness. These first naps typically occurred in response to acute sleep loss associated with overnight eastward flights or westward flights crossing five time zones or more. Other naps occurred just prior to the next duty period and effectively shortened the length of continuous wakefulness.

Crew members also reported in their logbooks the occurrence of naps on the flight deck. (In-flight rest on the flight deck is not sanctioned under current federal regulations.) The average duration of the naps reported on the flight deck was 46 min (range, 10–130 min). Research observers accompanying the crews also noted naps not reported in the logbooks. Data combining the research observers' notes and logbook data suggest that, on average, 11% of flight crew members were taking the opportunity to nap when conditions permitted. The data do not indicate whether these were planned naps or occurred spontaneously in response to sleep loss and circadian disruption.

This study provides unique insights into the physiological and subjective effects of flying long-haul commercial operations. The information is scientifically provocative and can be translated into operationally relevant considerations. The following are some of the scientific considerations that emerge from the results.

The flight schedules pushed the sleep/wake cycle into a period (25.7 h) different from that of the circadian system, though the two sys-

tems did not become completely uncoupled. Although the circadian system continued to influence the timing and duration of sleep episodes, it was unable to resynchronize and quickly adapt to the rapid, multiple time-zone shifts. It is clear that a variety of external/environmental factors (e.g., light, activity, social cues) interact with internal/physiological factors to affect sleep timing, duration, and quality. The operational relevance of the data is easy to discern. For example, current flight and duty time regulations are intended to ensure that reasonable minimum rest periods are available for flight crews. However, this study demonstrated that in commercial long-haul flight schedules, there are physiologically and environmentally determined preferred sleep times within a layover, and therefore the time available for sleep may be less than the off-duty time available.

Planned Cockpit Rest

As indicated from the results of the previous study, long-haul flight operations involve sleep loss and circadian disruption. Anecdotal, observational, and self-report sources (e.g., those from the previous study) indicate that sleep does occur on the flight deck, despite federal regulations forbidding in-flight rest. It is unclear from available data how often these naps are planned and how often they occur spontaneously in response to sleep loss and circadian disruption. In consideration of the available information regarding rest on the flight deck, the first test of an operational fatigue countermeasure was conducted. A NASA/FAA study examined the effectiveness of a planned cockpit rest period to maintain and/or improve subsequent performance and alertness in long-haul, nonaugmented international flights (nonaugmented = only primary crew required; augmented = extra crew needed when over certain flying times; Rosekind, et al., in press).

A regularly scheduled 12-day, eight-leg trip that involved multiple trans-Pacific crossings was selected for study. The flight legs averaged just over 9 h and were followed by about 25 h of layover. Prior to, during, and after the 12-day trip, crew members completed pilot's daily logbooks, documenting sleep and duty times and other activities, and wore actigraphs on their nondominant wrist. (An actigraph collects noninvasive activity data from a motion sensor, providing an estimate of an individual's 24-h rest/activity pattern; Cole, Kripke, Gruen, Mullaney, and Gillin, 1992.) The middle four legs of the trip schedule were studied intensively. EEG and EOG activity was continuously monitored during these flight legs using the Medilog recorder. An extensive scientific literature demonstrates that self-reports of sleep (e.g., time to fall asleep, total sleep time) do not accurately reflect physiological activity (Carskadon et al., 1976; Rosekind and Schwartz, 1988). Therefore it was critical to document the amount of physiological sleep obtained. Continuous EEG and EOG recordings taken during the awake period were used to assess physiological sleepiness. The PVT was used as a measure of vigilance performance and sustained attention. Pilots also gave self-report ratings of alertness and mood at predetermined times throughout the flight. Two NASA researchers traveled with the crews to implement the procedures and collect data.

The three-person Boeing 747 volunteer crew members were randomly assigned to either a rest group or no-rest group. Each rest group member (12 subjects) had a 40-min rest opportunity during the low-workload portion of flights over water. Crew members rested one at a time on a prearranged rotation while the other two crew members maintained the flight. The no-rest group (9 subjects) had a 40-min control period identified when they were instructed to continue their regular flight activities. Specific safety and proce-

dural guidelines were used during the study.

The first question was whether pilots would be able to sleep during a planned rest opportunity in their cockpit seat. The rest group slept during 93% of the rest opportunities. On average, they fell asleep in 5.6 mins and slept for about 26 min. Whether or not a benefit was associated with this sleep was determined by examining the vigilance performance measure and indicators of physiological sleepiness. As expected, the no-rest group showed performance decrements (i.e., increased reaction times and variability on the PVT) at the end of flights compared with the beginning of flights, on night flights versus day flights, and on the fourth study leg compared with the first study leg. The rest group, however, demonstrated positive effects of the brief nap by maintaining consistently good performance at the end of flights, on night flights, and on the fourth study leg.

Physiological sleepiness was examined by evaluating the subtle EEG and EOG changes that indicate state lability. Previous research has demonstrated that physiological sleepiness is associated with the occurrence of EEG alpha or theta waves and/or EOG slow eye movements. These physiological events are associated with decreased performance (Akerstedt, 1992; Akerstedt and Gillberg, 1990). Microevents (brief sleep events) indicative of physiological sleepiness (the occurrence of EEG alpha or theta waves and/or EOG slow eye movements) lasting 5 s or longer were identified during the last 90 min of flight, even during descent and landing, in both study groups. Overall, the no-rest group had microevents (mean = 6.37) indicative of physiological sleepiness at a rate twice that of the rest group (mean = 2.90).

The brief nap appeared to act as an acute in-flight operational safety valve and did not affect the cumulative sleep debt observed in 85% of the crew members. The rest group members were usually able to sleep during

the rest opportunity, and this nap was associated with improved performance and alertness compared with the no-rest control group. This was the first empirical test of a fatigue countermeasure conducted in an operational aviation setting that combined physiological, performance, and subjective measures.

Not only are the results scientifically interesting, but they can be transferred directly into operational considerations regarding planned rest. Based partly on the results of this NASA/FAA study, an industry/government working group has drafted an advisory circular for review by the FAA's Aviation Rulemaking Advisory Committee. The circular outlines specific guidelines for the development and implementation of a program for controlled rest on the flight deck. It should be noted that controlled rest is only one in-flight countermeasure and is not the panacea for all of the sleep loss and circadian disruption engendered by long-haul flight operations (Rosekind, Gander, and Dinges, 1991).

Current Activities and Future Directions

In 1991, the name of the program was changed to the Fatigue Countermeasures Program to emphasize the development and evaluation of countermeasures. One area of intense activity is the analysis and writing of a variety of scientific and operational publications to transfer the information acquired over the past 12 years to the scientific and operational communities. Another project involves a study of the onboard crew rest facilities on long-haul aircraft. Bunks are available for pilots when a flight is augmented (extra crew onboard) and the flight length extends beyond that allowed for a single crew. This study will examine the quantity and quality of sleep obtained in onboard crew rest facilities, the factors that promote or interfere with sleep, and the effects on subsequent performance and alertness.

Another major project is the development and implementation of an education and training module entitled "Alertness Management in Flight Operations" (Rosekind, Gander, and Connell, in press). It provides information on physiological sources of fatigue and how flight operations affect these factors and makes recommendations for fatigue countermeasures. The module is intended for any interested party in the aviation community, including pilots, air carrier managers, schedulers, flight attendants, and federal policymakers. Potential areas for future program activity include the development of an expert scheduling system that incorporates known scientific and physiological data, an examination of fatigue in regional airline operations, and further development and evaluation of countermeasures.

FUTURE CONSIDERATIONS FOR FATIGUE RESEARCH IN OPERATIONAL SETTINGS

As issues of safety and health continue to be raised regarding fatigue in operational environments, more research will be required to address them. Major questions raised in many operational settings include, What is safe? How long is too long to drive, fly, or operate a train? How many night shifts in a row is too many? How long is too long for a shift period? How many consecutive days can be worked safely? How long does it take to recover after an extended duty or shift period? How long does it take to recover after several consecutive duty or shift periods? Do individuals need one night of sleep or two nights? How could naps be used to improve the situation? How should one define recovery: by physiological adaptation, performance, or waking sleepiness? After starting a new shift schedule, how long will it take to physiologically adapt? What are the effects of changing from a night shift schedule to a regular daytime schedule on the weekends and

then back to night shifts? How should current hours-of-service regulations be evaluated? If they should be changed, how should they be adjusted? On what should such changes be based?

Each of the issues raised suggests a wide range of research activities. They also represent the concerns faced by the 20 million Americans currently working altered or non-standard shifts. The point of these questions is that the scientific research will be most useful if it is integrated with operational concerns.

There are other considerations as well. Although generic research will help to set a scientific foundation for addressing these operational questions, it is also critical to understand the specific requirements of different settings. The type of shift schedule, task demands, timing of critical tasks, and other factors such as meal availability and break schedules present different challenges. Another area to examine is the tremendous individual variation that exists in response to sleep loss, circadian disruption, and performance changes. Different work and corporate cultures will have disparate attitudes, knowledge, and concern about these issues, and this can affect work performance and satisfaction. Also, there is very little information regarding the long-term (e.g., months or years) effects of sleep loss and circadian disruption on safety, performance, productivity, and health. Another major area is the development and empirical evaluation of countermeasures. There may be a wide variety of solutions that will maximize alertness and performance—for instance, those involving physiological strategies, display design, or schedule design. This area creates tremendous potential for evaluating new technologies and strategies.

One valuable approach is to coordinate and integrate resources and expertise among researchers, federal agencies, policymakers,

and so on to maximize the potential effect of any given research project or operational implementation of findings. It is often critical that scientists be allowed access to the subjects' operational environment or, at minimum, to fully understand how things work in a particular setting. The close coordination of scientific and operational efforts can also lay the foundation for a direct application of positive findings.

Clearly there is a lot of important work to be done. The NASA Ames Fatigue Countermeasures Program is presented as a model of one approach to addressing some of the issues raised. It is not the only approach possible but is presented to stimulate empirical research in applied operational settings.

Human factors research can play a pivotal role in the scientific investigation of these issues and in the application of the findings to specific operational questions. As long as 24-h operations are required to maintain societal needs, the effects of sleep loss and circadian disruption must be considerations in any operational setting. How these factors affect the physiological and performance capabilities of the human operator will be critical to job safety, performance, and productivity.

ACKNOWLEDGMENTS

We wish to acknowledge the significant contributions of the following: John Lauber, Curt Graeber, Clay Foushee, and Charles Billings; William Reynard and Linda Connell at NASA Ames; Key Dismukes for a thorough and constructive manuscript review; David Dinges, Institute for Pennsylvania Hospital/University of Pennsylvania School of Medicine, for ongoing collaboration; and the FAA staff, volunteer pilots, air carriers, and unions, who have been critical to the success of program activities.

APPENDIX: FATIGUE COUNTERMEASURES PROGRAM REFERENCES (PARTIAL LISTING)

- Dinges, D. F., and Graeber, R. C. (1989, October). Crew fatigue monitoring. *Flight Safety Digest*, (Suppl.), 65–75.
- Dinges, D. F., Connell, L. J., Rosekind, M. R., Gillen, K. A., Kribbs, N. B., and Graeber, R. C. (1991). Effects of cockpit naps and 24-h layovers on sleep debt in long-haul transmeridian flight crews. *Sleep Research*, 20, 406. (Abstract)

- Dinges, D. F., Graeber, R. C., Connell, L. J., Rosekind, M. R., and Powell, J. W. (1990). Fatigue-related reaction time performance in long-haul flight crews. *Sleep Research*, 19, 117. (Abstract)
- Dinges, D. F., Rosekind, M. R., Connell, L. J., Graeber, R. C., and Gillen, K. A. (1992). Eastbound night flights vs. westbound day flights: Directionally dependent effects on flight crew layover sleep. *Sleep Research*, 21, 118. (Abstract)
- Foushee, H. C., Lauber, J. K., Baetge, M. M. and Acombe, D. B. (1986). *Crew factors in flight operations: III. The operational significance of exposure to short-haul air transport operations* (Tech. Memorandum 88322). Moffett Field, CA: National Aeronautics and Space Administration.
- Gander, P. H., Barnes, R., Gregory, K. B., Connell, L. J., Miller, D. L., and Graeber, R. C. (in press). *Crew factors in flight operations: VII. Psychophysiological responses to helicopter operations* (Tech. Memorandum). Moffett Field, CA: National Aeronautics and Space Administration.
- Gander, P. H., Connell, L. J., and Graeber, R. C. (1986). Masking of the circadian rhythms of heart rate and core body temperature by the rest-activity cycle in man. *Journal of Biological Rhythms Research*, 1, 119–135.
- Gander, P. H., and Graeber, R. C. (1987). Sleep in pilots flying short-haul commercial schedules. *Ergonomics*, 30, 1365–1377.
- Gander, P. H., Gregory, K. B., Connell, L. J., Miller, D. L., and Graeber, R. C. (in press). *Crew factors in flight operations: VII. Psychophysiological responses to overnight cargo operations* (Tech. Memorandum). Moffett Field, CA: National Aeronautics and Space Administration.
- Gander, P. H., Kronauer, R., and Graeber, R. C. (1985). Phase-shifting two coupled circadian pacemakers: Implications for jetlag. *American Journal of Physiology*, 249, R704–R719.
- Gander, P. H., McDonald, J. A., Montgomery, J. C., and Paulin, M. G. (1991). Adaptation of sleep and circadian rhythms to the Antarctic summer: A question of zeitgeber strength? *Aviation, Space and Environmental Medicine*, 62, 1019–1025.
- Gander, P. H., Myrhe, G., Graeber, R. C., Anderson, H. T., and Lauber, J. K. (1989). Adjustment of sleep and the circadian temperature rhythm after flights across nine time zones. *Aviation, Space and Environmental Medicine*, 60, 733–743.
- Gander, P. H., Nguyen, D., Rosekind, M. R., and Connell, L. J. (1993). Age, circadian rhythms, and sleep loss in flight crews. *Aviation, Space and Environmental Medicine*, 64, 189–195.
- Gander, P. H., and Samel, A. (1991). Shiftwork in space: Bright light as a chronobiologic countermeasure (SAE Tech. Paper 911496). Salem, MA: Society of Automotive Engineers.
- Graeber, R. C. (1982). Alterations in performance following rapid transmeridian flight. In F. M. Brown and R. C. Graeber (Eds.), *Rhythmic aspects of behavior* (pp. 172–212). Hillsdale, NJ: Erlbaum.
- Graeber, R. C. (Ed.). (1986). *Crew factors in flight operations: IV. Sleep and wakefulness in international aircrews* (Tech. Memorandum 88231). Moffett Field, CA: National Aeronautics and Space Administration.
- Graeber, R. C. (1988). Aircrew fatigue and circadian rhythmicity. In E. Wiener and D. Nagel (Eds.), *Human factors in aviation* (pp. 305–344). New York: Academic.
- Graeber, R. C. (1989). Jet lag and sleep disruption. In M. H. Kryger, T. Roth, and W. C. Dement (Eds.), *Principles and practice of sleep medicine*. Philadelphia: Harcourt Brace Jovanovich.
- Graeber, R. C., Foushee, C., Gander, P. H., and Noga, G. (1985). Circadian rhythmicity and fatigue in flight operations. *Journal of Occupational and Environmental Health*, 7(Suppl.), 122–129.
- Graeber, R. C., Foushee, C., and Lauber, J. (1984). Dimensions of flight crew performance decrements: Methodological implications for field research. In J. Cullen and J. Siegrist (Eds.), *Breakdown in human adaptation to stress* (pp. 584–605). Boston: Martinus Nijhoff.
- Kurosaki, Y., Sasaki, M., Takahashi, T., Mori, A., Spinweller, C. L., and Graeber, R. C. (1987). Flight crew sleep after multiple layover polar flights. *Sleep Research*, 16, 565. (Abstract)
- Monk, T., Moline, M., and Graeber, R. C. (1988). Inducing jet lag in the laboratory: Patterns of adjustment to an acute shift in routine. *Aviation, Space and Environmental Medicine*, 59, 703–710.
- Rosekind, M. R. (1992). Pilots. In M. A. Carskadon (Ed.), *The encyclopedia of sleep and dreaming*. New York: Macmillan.
- Rosekind, M. R., Dinges, D. F., Gregory, K. B., Gillen, K. A., Smith, R. M., Powell, J. W., and Miller, D. L. (1993). Estimating nap sleep in operational settings: A comparison of actigraphy vs. ambulatory polysomnography. *Sleep Research*, 22, 380. (Abstract)
- Rosekind, M. R., Gander, P. H., Miller, D. L., Gregory, K. B., McNally, K. L., Smith, R. M., and Lebacqz, J. V. (1993). NASA Ames fatigue countermeasures program. *FAA Aviation Safety Journal*, 3(1), 20–25.
- Samel, A., and Gander, P. H. (Eds.). (1991). *Light as a chronobiologic countermeasure for long-duration space operations* (Tech. Memorandum 103874). Moffett Field, CA: National Aeronautics and Space Administration.

REFERENCES

- Akerstedt, T. (1991). Sleepiness at work: Effects of irregular work hours. In T. Monk (Ed.), *Sleep, sleepiness, and performance* (pp. 129–152). Chichester, England: Wiley.
- Akerstedt, T. (1992). Work hours and continuous monitoring of sleepiness. In R. J. Broughton and R. D. Ogilvie (Eds.), *Sleep, arousal, and performance* (pp. 63–72). Boston: Birkhauser.
- Akerstedt, T., and Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, 52, 29–37.
- Bonnett, M. H. (1985). The effect of sleep disruption on performance, sleep, and mood. *Sleep*, 8, 11–19.
- Broughton, R. J., and Ogilvie, R. D. (Eds.). (1992). *Sleep, arousal, and performance*. Boston: Birkhäuser.
- Carskadon, M. A., and Dement, W. C. (1982). Nocturnal determinants of daytime sleepiness. *Sleep*, 5, S73–S81.
- Carskadon, M. A., Dement, W. C., Mitler, M. M., Guilleminault, C., Zarcone, V. P., and Spiegel, R. (1976). Self-reports versus sleep laboratory findings in 122 drug-free subjects with complaints of chronic insomnia. *American Journal of Psychiatry*, 133, 1382–1388.
- Cole, R. J., Kripke, D. F., Gruen, W., Mullaney, D. J., and Gillin, J. C. (1992). Automatic sleep/wake identification from wrist activity. *Sleep*, 15, 461–469.
- Dinges, D. F. (1989). The influence of the human circadian time keeping system on sleep. In M. H. Kryger, T. Roth,

- and W. C. Dement (Eds.), *Principles and practice of sleep medicine* (pp. 153–162). Philadelphia: W.B. Saunders.
- Dinges, D. F., and Kribbs, N. B. (1991). Performing while sleepy: Effects of experimentally induced sleepiness. In T. Monk (Ed.), *Sleep, sleepiness, and performance* (pp. 97–128). Chichester, England: Wiley.
- Dinges, D. F., and Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments and Computers*, 17, 652–655.
- Dinges, D. F., and Powell, J. W. (1988). Sleepiness is more than lapsing. *Sleep Research*, 17, 84. (Abstract)
- Gander, P. H., Graeber, R. C., Connell, L. J., and Gregory, K. B. (1991). *Crew factors in flight operations: VIII. Factors influencing sleep timing and subjective sleep quality in commercial long-haul flight crews* (Tech. Memorandum 103852). Moffett Field, CA: National Aeronautics and Space Administration.
- Gander, P. H., Graeber, R. C., Foushee, H. C., Lauber, J. K., and Connell, L. J. (in press). *Crew factors in flight operations: II. Psychophysiological responses to short-haul air transport operations* (Tech. Memorandum 88321). Moffett Field, CA: National Aeronautics and Space Administration.
- Mistlberger, R., and Rusak, B. (1989). Mechanisms and models of the circadian timekeeping system. In M. H. Kryger, T. Roth, and W. C. Dement (Eds.), *Principles and practice of sleep medicine* (pp. 141–152). Philadelphia: W.B. Saunders.
- Monk, T. H. (1989). Circadian rhythms in subjective activation, mood, and performance efficiency. In M. H. Kryger, T. Roth, and W. C. Dement (Eds.), *Principles and practice of sleep medicine* (pp. 163–172). Philadelphia: W.B. Saunders.
- National Aeronautics and Space Administration. (1980). *Pilot fatigue and circadian desynchronis* (Report of a workshop held in San Francisco, California, on August 26–28, 1980; Tech. Memorandum 81275). Moffett Field, CA: Author.
- Office of Technology Assessment. (1991, September). *Biological rhythms: Implications for the worker* (OTA-BA-463). Washington, DC: U.S. Government Printing Office.
- Rosekind, M. R., Gander, P. H., and Connell, L. J. (in press). *Crew factors in flight operations: X. Alertness management in flight operations* (Tech. Memorandum). Moffett Field, CA: National Aeronautics and Space Administration.
- Rosekind, M. R., Gander, P. H., and Dinges, D. F. (1991). *Alertness management in flight operations: Strategic napping* (SAE Tech. Paper Series 912138). Salem, MA: Society of Automotive Engineers.
- Rosekind, M. R., Graeber, R. C., Dinges, D. F., Connell, L. J., Rountree, M. S., Spinweber, C. L., and Gillen, K. A. (in press). *Crew factors in flight operations: IX. Effects of planned cockpit rest on crew performance and alertness in long-haul operations* (Tech. Memorandum 103884). Moffett Field, CA: National Aeronautics and Space Administration.
- Rosekind, M. R., and Schwartz, G. E. (1988). The perception of sleep and wakefulness: I. Accuracy and certainty of subjective judgments. *Sleep Research*, 17, 89. (Abstract)
- Roth, T., Roehrs, T. A., Carskadon, M. A., and Dement, W. C. (1989). Daytime sleepiness and alertness. In M. H. Kryger, T. Roth, and W. C. Dement (Eds.), *Principles and practice of sleep medicine* (pp. 14–23). Philadelphia: W.B. Saunders.

Date received: January 25, 1993

Date accepted: July 22, 1993